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POSSIBILITIES AND LIMITATIONS OF VIBRATION REDUCTION AT THE PROPAGATION PATH

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ABSTRACT

Real Estate Developments in the proximity of existing railway lines usually lead to additional demands on the planning and execution of the project. In addition to effects such as electric/electromagnetic fields or noise, vibrations and the resulting structure-borne noise can also represent a cost-relevant aspect during planning and execution. The implementation of track-side measures is especially at existing railway lines not possible. Therefore, measures at the building or at the propagation path (subsoil) must be considered. Measures on the building, such as elastic building bearings, are difficult to implement in complex building structures. In addition, the high insulation effects achieved by elastic building bearings are often not necessary, so that alternative, more cost-effective measures are considered.

In the present study, measures at the propagation path are examined. Diaphragm walls, pile walls are examined based on numerical model calculations. Such civil engineering measures must be sometimes constructed anyway partly for constructional reasons, e.g., for excavation protection. The investigations are carried out based on numerical model calculations with the FLAC software. The aim of the present work is to investigate the effectiveness of different measures in the subsoil in the light of geological boundary conditions.

Keywords— railway vibration, propagation, reduction

1. INTRODUCTION

Developments in the area of individual mobility and the associated need for highly available public transport possibilities lead on the one hand to an accelerated expansion of public transport and on the other hand to the fact that real estate developments are oriented towards public transport. For this purpose, areas in the vicinity of railroad lines, in particular railroad stations, are released for development. However, this proximity to public transport, in particular to railway lines, also entails disadvantages with regard to possible immissions from vibrations or re-radiated noise. In addition, the constructional boundary conditions, such as noise protection windows, lead to the fact that the base noise levels in the living rooms are low and externally immitted immissions, especially re-radiated noise, come more to the fore.

Measures to reduce vibration and secondary noise emissions are conceivable at emission side (track side), at propagation path or at the building itself. In the case of newly constructed lines, the most efficient method of reducing emissions is to use appropriate measures (under-ballast mats, under-sleeper pads or mass-spring systems). In case of new residential buildings in vicinity of existing railway lines, it is possible to consider measures at the building itself. These can consist in the reinforcement of individual components (e.g., foundation slab) but also in the partial or complete elastic bearing below the foundation.

In special situations, however, e.g., when existing objects along the railroad are to be renovated or upgraded, it may not be possible to take measures on either the existing building or the railway line. In such cases, it is possible to consider measures at the propagation path.

The present work examines the possibilities and limits of this measure based on numerical simulations. The aim is to define boundary conditions for the modelling and to describe the possible vibration reduction.

2. PRINCIPLES

The rolling load over the rails generates alternating force effects which propagate over the superstructure and substructure into the subsoil as vibrations.
In the ideal half-space, two major types of waves are generated by an excitation at the surface - as shown in figure 1 [1]. They are *(a)* body waves, which propagate hemispherical into the depth and (b) surface waves, which - like water waves - propagate on the surface (with limited depth effect). The first category consists of compression and shear waves, to the second belong mainly the Rayleigh waves.

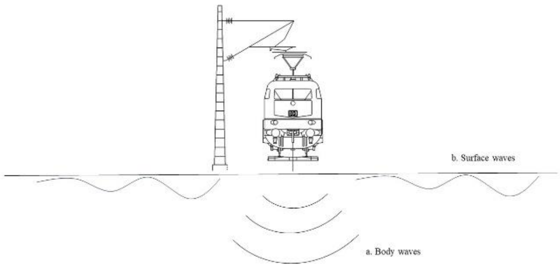

Figure 1: Major types of waves

An analytical calculation of the vibration propagation can be performed considering eq. 1 and the two auxiliary variables of eq. 2 and eq. 3.

$$v = v_1 \left(\frac{R}{R_1}\right)^{-n} exp\left[\left(-\alpha(R - R_1)\right)\right] \quad (1)$$

$$R_1 \approx \frac{a}{2} + \lambda_R \quad (2)$$

$$\alpha \approx \frac{2\pi D}{\lambda} \quad (3)$$

Where v or v_1 is the vibration velocity at the distance R or the reference distance R_1, D is the material damping, and λ is the wavelength of the relevant waveform. The exponent n is the parameter which describes the geometric propagation of the corresponding waveform in an ideal half-space. The corresponding values for n, depending on the waveform or the excitation characteristic, can be found in Table 1.

Table 1: Wave propagation in ideal half space

wave type	vibration reduction point source	vibration reduction line source
body wave on surface	$v = v_0 \left(\frac{r_0}{r}\right)^2$	$v = v_0 \left(\frac{r_0}{r}\right)^1$
surface wave	$v = v_0 \left(\frac{r_0}{r}\right)^{0.5}$	$v = v_0 \left(\frac{r_0}{r}\right)^0$

Body waves of a point source shows the strongest decrease, while surface waves of a line source, related to the purely geometric damping in an ideal half-space, continues unchanged.

3. NUMERICAL CALCULATIONS

3.1. Program package *Flac*

For the numerical investigations, the software package Flac from Itasca in version 8.0 was used. *Flac* is a finite difference program for solving static, dynamic and geothermal problems.

Load application/vibration excitation in the model was performed on the surface. A *Sinc* function was chosen therefore with an excitation frequency range of 1-200Hz and a duration of 0.02s. Figure 2 shows a graphical representation of the time history of the *Sinc* function used.

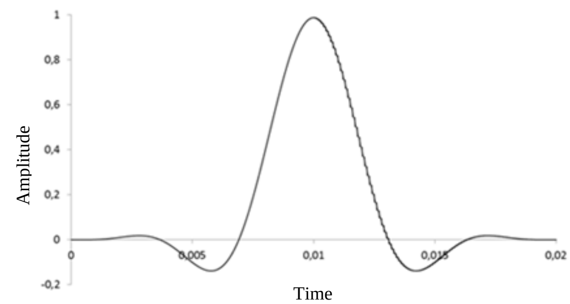

Figure 2: Time course representation of the Sinc impulse.

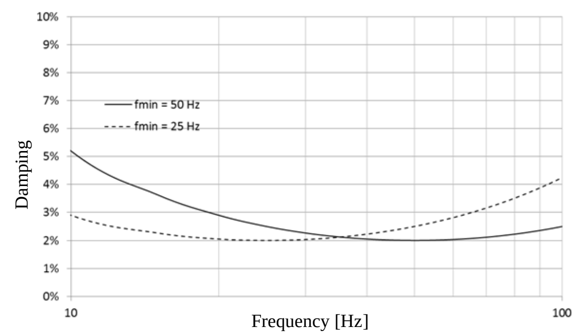

Figure 3: Rayleigh damping f_{min} from 50Hz to 25Hz.

Rayleigh damping was assumed as the damping approach in the simulations. The parameters for the Rayleigh damping were assumed to be 2% at f_{min}=25Hz (ground) and 50Hz (concrete). This means that the previously assumed damping is given at the respective frequency f_{min}, or the minimum damping occurs in this range (cf. Figure 2).

3.2. Calculation Model

A standard situation of a railway line on surface was chosen as the calculation model (Figure 3). The load introduction in the model was carried out at the surface. A concrete wall was realized in the model at the propagation path. The depth of the concrete wall and the thickness was varied in the simulation calculations.

Since there is no rigid connection between the soil and the concrete wall, an element row (10cm) with a softer layer was assumed in the model (Figure 4 and Table 2).

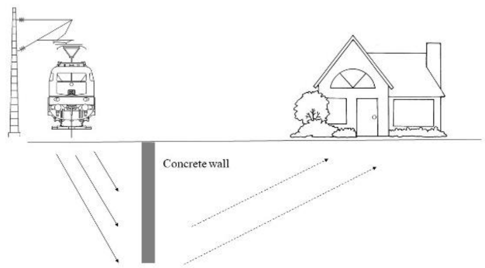

Figure 1: Modelling situation.

The model dimensions themselves are 100m and 60m in depth. The element size was chosen with 10cm, so that frequencies up to 100Hz can be adequately resolved at the given wave velocities in any case. The approach was followed that at least 4-5 elements were given for one wavelength [2].
As geological/geodynamic boundary conditions a homogeneous half-space with the parameters given in table 2 was assumed.

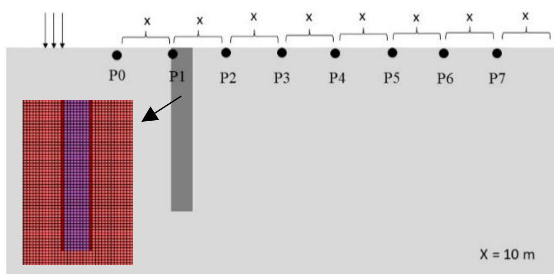

Figure 2: Calculation Model.

In total, the simulation results were collected at 8 calculation points (P0 to P7). At each of these calculation points, the results from 3 different node points were averaged. The calculation points themselves were chosen 2m below the ground surface. This is to reflect the situation of a building foundation.

The dynamic calculation itself takes place over 0.8s. This was chosen in such a way that even the slowest wave, the Rayleigh wave, passed through the model dimensions in any case.

Table 2: Geodynamic parameters of the model

	density	c_p	c_s	K_{dyn}	G_{dyn}
	[kg/m^3]	[m/s]	[m/s]	[MPA]	[MPA]
half space	1.900	1400	700	248	93
reduced zone	190	140	70	24	9,5
concrete	2500	4200	2500	23200	15630

The evaluation of the calculation data at the individual calculation points (P0 to P7) was carried out with the program package *Octave*. Both the maximum values within the 0.8s calculation time and the one-third octave band spectra for each calculation point were evaluated.

The following situations were simulated withing the present work:

- concrete wall thickness of 60cm and 80cm respectively
- concrete wall depths of 5m, 8m, 15m and 20m
- 4 different subsoil parameters

The results and interpretations of the simulations are given in the following sections. The indicated distances of the individual calculation points refer to the source in each case.

3.3. Simulation Result

3.3.1. Influence of the concrete wall thickness

To determine the influence of the thickness of the concrete wall, simulations were carried out with two different thicknesses (60cm and 80cm). These thicknesses were chosen based on the usual design thicknesses of piles and diaphragm walls, respectively.

The results of the comparison show that the differences between the two investigated concrete wall thicknesses are relatively small (12-14%) and occur mainly at frequencies between 30-60Hz. Outside this frequency range, no significant differences between the two investigated variants can be observed.

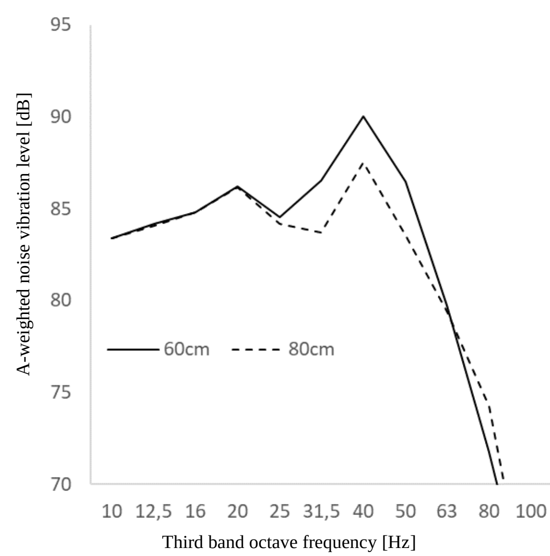

Figure 3: Comparison 60cm vs. 80cm concrete wall.

3.3.2. Influence of the concrete wall depth

Another goal of the present work is to show the influence of the length (depth) of the concrete wall to vibration reduction. In past works [3]-[5] it is pointed out that the depth of concrete walls has a significant influence on the effectiveness in terms of vibration reduction. In addition, [3]-[5] show that vibration reductions of up to 10dB are possible in higher frequencies.

From the field test at [4] it could be concluded that such a measure is only effective if the depth of the concrete wall is greater than the existing Rayleigh wavelength. From this it is already clear that, considering Eq. 4, the effect of this measure depends on the given wave velocities, in particular the Rayleigh wave velocity, and on the frequencies occurring.

$$\lambda = \frac{c}{f} \tag{4}$$

Figure 7 shows an overview of the vibration maxima at different distances from the source both for the model without concrete wall and for the different depths of the concrete wall. The vibration maxima are shown as levels (*$v_{ref}=5*10^{-8}m/s$*). In addition, Fig. 5 shows the A-weighted [6], [7] vibration levels. This gives information about the vibration reduction in the audible range of the vibrations.

The results generally show that all investigated variants lead to a reduction of vibrations compared to the model without concrete wall. Depending on the distance to the source or the depth of the concrete wall, there is a reduction of 5-10dB. Regarding the A-weighted vibration levels which represent the audible part of the vibrations there are improvements of up to 20dB. The results further show that, the depth of the concrete wall has a significant influence on the vibration reduction. Especially regarding the A-weighted vibration levels, the depth shows a direct correlation with the determined A-weighted vibration levels in the entire investigated distance range to the source (fig. 7).

Regarding the unweighted vibration levels, the influence of the depth of the concrete wall increases with increasing distance from the source. In the range of about 30m, no significant differences of the investigated concrete wall depths of 5 and 8 m on the vibration reduction can be detected.

Fig. 8 shows a frequency analysis for 50m distance to the source. According to acoustics one-third octave bands were chosen.

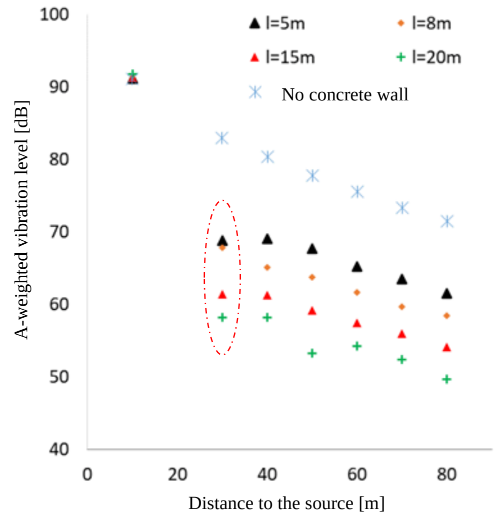

Figure 4: Overview simulation results A-weighted.

The frequency-related results of Fig 8 show that in the very low-frequency range up to about 20Hz only minor differences of the individual concrete wall depths can be observed. Des is probably due to the wavelengths of the governing waveforms.

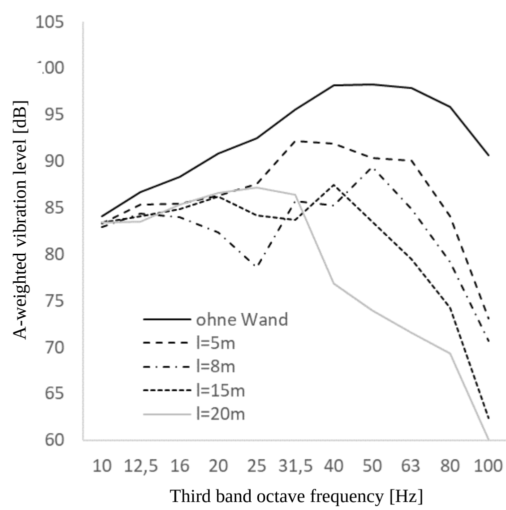

Figure 5: Frequency analyses for the distance of 50m.

According to Eq. 4, the wave velocity of the Rayleigh waves c_R can be estimated from the heavy wave velocity cs.

$$c_R = \frac{0.87 + 1.12\nu}{1 + \nu} c_S \tag{5}$$

Based on the knowledge of the wave velocities of the individual wave types, the frequency-dependent wavelengths can be determined according to Eq. 4 (Fig. 9).

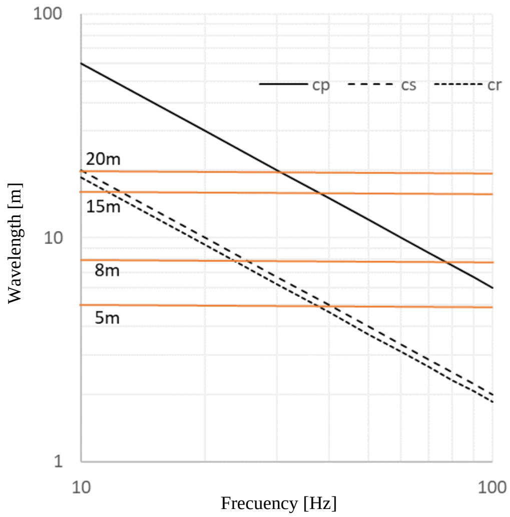

Figure 6: Frequency-dependent wavelengths of individual wave types

It is noted in [4] that the wavelength of the Rayleigh waveform is the decisive parameter for the effectiveness of a concrete wall in the subsurface. This means for the present simulations that already the concrete wall with a depth of 5m reaches the order of magnitude of the wavelength from a frequency of about 30Hz and leads to a significant vibration reduction. This can only be rudimentarily read out from the results in Figure 7. The reason for this is probably to be found in the depth extension of the Rayleigh waves or in the location of the calculation points (2m below ground level). Rayleigh wave amplitudes decrease rapidly with depth, so that at greater depths other waveforms may dominate. Compression waves, for example, have a much higher propagation speed and thus generally longer wavelengths. It can therefore be assumed that the effectiveness, which only begins at higher frequencies than assumed, is due to this circumstance.

Overall, however, the results of Fig. 7 in the higher frequency range show the expected results about increasing vibration reduction with increasing concrete wall depth.

3.3.3. Influence of the subsoil parameters

After examining the influence of the depth and thickness of the concrete wall in the previous sections, this section aims to demonstrate the impact of the substrate parameters on the effectiveness of the concrete wall as a shield.

For this purpose, one of the previously calculated models was chosen. In particular, the calculation model was used in which the concrete wall was 15m deep and with a thickness of 80cm.

To examine the influence four different types of geodynamic subsoil parameters were applied in the model.

Table 3 shows a summary of the parameters used for the present calculations.

Table 3: Geodynamic parameters of the model

	density [kg/m³]	c_p [m/s]	c_s [m/s]	K_{dyn} [MPA]	G_{dyn} [MPA]
Case A					
half space	1.650	300	110	121	19
Case B					
half space	1.900	1400	700	248	93
Case C					
half space	2000	1800	900	432	162
Case D					
half space	2100	2000	950	587	190

As Table 3 clearly indicates, both very soft substrate parameters, such as those found in a top layer of the subsoil, and very stiff soil parameters were investigated.

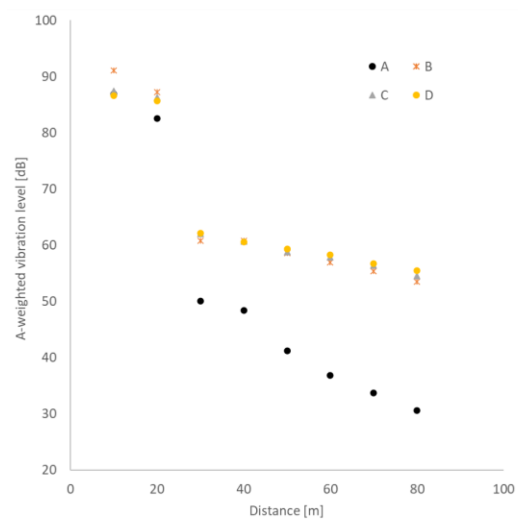

Figure 7: Results overview geodynamic parameters

From the results depicted in Figure 7, it is evident that the very soft layer parameters result in high insulation effects. This is certainly due, on the one hand, to the overall poorer transmission of vibrations through the soft layer, but on the other hand, it is also attributed to the significant stiffness contrast between the soft layer and the concrete wall.

The further examined subsoil parameters show a rather comparable behaviour considering the A-weighted vibration level. Figure 8 shows the frequency spectres of the transfer functions for the observation point at 60m.

In the low frequencies, up to approx. 20Hz the results are comparable. Above 20Hz a significant difference in the transfer function can be observed.

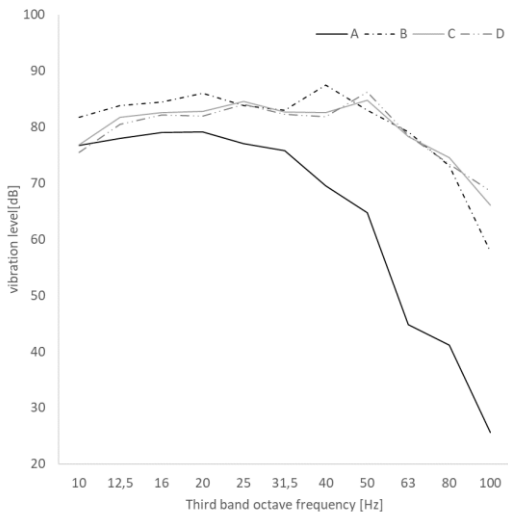

Figure 8: Geodynamic parameters comparation at 60m

The result of the present section shows that, especially for soft soils, there is a significant difference in the vibration damping behavior for the concrete wall.

This effect can primarily be attributed to the higher stiffness contrast between the substrate and the concrete wall. Additionally, there is also the effect that the softer soil layer generally exhibits poorer vibration transmission in the higher-frequency range.

4. SUMMARY AND OUTLOOK

This study gives an overview of the possibilities to reduce vibrations by means of underground wave barriers (e.g., bored pile walls or diaphragm walls). For this purpose, different variants of concrete walls in the subsoil were investigated using a calculation model and evaluated regarding vibration reduction.

In summary, it can be said that significant vibration reduction can be achieved by such measures. In the range of perceptible vibrations, reductions of 5-10 dB can be achieved, depending on the distance to the source and the depth of the measure. In the secondary sound range (A-weighted sum level), improvements of up to 20 dB are possible. However, the simulations also show that the depth of the measure has a considerable influence on the frequency range from which a significant reduction occurs and on the amount of reduction itself.

In any case, the minimum depth for the measure is the length of the wavelength of the relevant wave type (cf. Figure 9). However, this is to be regarded as an absolute lower limit; rather, it must be considered that other wave forms with partly longer wavelengths can be decisive in the subsurface.

In the present study, a homogeneous half-space was used as the basis for the simulation since the aim was merely to show basic relationships and dependencies. In practice, the planning of such measures will be confronted with more complex soil dynamic boundary conditions such as multi-layer structures. A detailed design can therefore only be carried out in individual cases based on the existing soil structures.

Since concrete is an energy-intensive building material, it would be desirable to investigate alternative building materials such as wood or plastic installations or hybrid variants for further studies in this area. In any case, it must be considered that there must be a sufficient difference in stiffness (both positive and negative) between the surrounding soil and the measure itself to achieve significant reductions.

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